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A decrease in the sink for atmospheric CO_2 in the North Atlantic

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[1] Global ocean carbon models and available syntheses of the oceanic CO_2 flux suggest that the North Atlantic subpolar gyre (50°N–70°N, 80°W–10°W) is a region of increasing uptake of CO_2 from the atmosphere, with the oceanic partial pressure of CO_2 (pCO_2) increasing more slowly than the atmospheric CO_2 over time. Our analysis of available CO_2 data shows that, on the contrary, seawater pCO_2 has increased faster than the atmosphere in recent decades, especially in summer, resulting in a decrease in uptake from the atmosphere. A decrease in the biological productivity of the region may be the underlying cause of this trend. From the observed trend we estimated a significant decrease in the annual carbon uptake in this region. *INDEX TERMS:* 4806 Oceanography: Biological and Chemical: Carbon cycling; 1615 Global Change: Biogeochemical processes (4805); 1635 Global Change: Oceans (4203); 4820 Oceanography: Biological and Chemical: Gases. **Citation:** Lefèvre, N., A. J. Watson, A. Olsen, A. F. Ríos, F. F. Pérez, and T. Johannessen (2004), A decrease in the sink for atmospheric CO_2 in the North Atlantic, *Geophys. Res. Lett.*, *31*, L07306, doi:10.1029/2003GL018957.

1. Introduction

[2] Ocean carbon cycle models predict that there is a large and increasing uptake of carbon dioxide across the air-sea interface in the North Atlantic [*Orr et al.*, 2001]. This is also the assumption made in CO_2 flux climatologies poleward of 45°N [e.g., *Takahashi et al.*, 2002]. Assuming that the wind field has remained constant, the sea-surface pCO_2 should have increased more slowly than the atmospheric pCO_2 since the industrial revolution.

[3] The lack of relevant observations has hindered an assessment of temporal trends in pCO_2 except at specific time-series stations such as the Bermuda Atlantic Time-Series Station (BATS) [*Bates*, 2001]. However, the possibility of measuring oceanic and atmospheric pCO_2 underway and autonomously has significantly increased the number of CO_2 measurements. As part of the European project CAVASSOO (Carbon Variability Studies by Ships of Opportunity), available CO_2 data have been gathered in a relational database for the North Atlantic Ocean, which includes over 220 cruises carried out from 1981 to present. We used this database to examine the temporal evolution of seawater pCO_2 in the North Atlantic subpolar gyre (50°N–70°N, 80°W–10°W) where over 100,000 underway seawater pCO_2 measurements have been collected during 1981–1998.

2. Methods

[4] Available CO_2 data are unevenly distributed in both space and time, even for the relatively well- sampled North Atlantic. In order to obtain unbiased estimates, one approach would be to determine robust empirical relationships that allow interpolation in time and space. Such relationships are unlikely to be valid over the entire ocean basin, given the complexity of the oceanic pCO_2 variability. Thus, we have subdivided the North Atlantic into smaller regions where the seawater pCO_2 can be considered as subject to the same processes. We used the biogeographical provinces of *Longhurst et al.* [1995] for this purpose. The subpolar gyre is then divided into 3 main provinces: the North Atlantic Drift (NADR, between 44°–58°N and 42°–10°W), the Subarctic (SARC, between 58°–66°N and 24°–10°W) and the Arctic (ARCT, the remaining between 50°–70°N and 60°–10°W) regions as shown in Figure 1.

[5] In each biogeochemical province (NADR, SARC and ARCT), the data were grouped by month. First, the thermodynamic influence on sea surface pCO_2 was removed by normalising to the monthly mean temperature, $(pCO_2)_T$, using the relationship suggested by *Takahashi et al.* [1993] for this purpose. The normalised pCO_2 behaves as total dissolved inorganic carbon and has a strong correlation with temperature in the North Atlantic as shown by previous studies [e.g., *Hood et al.*, 1999]. Then, we performed a multivariable linear regression between this normalised

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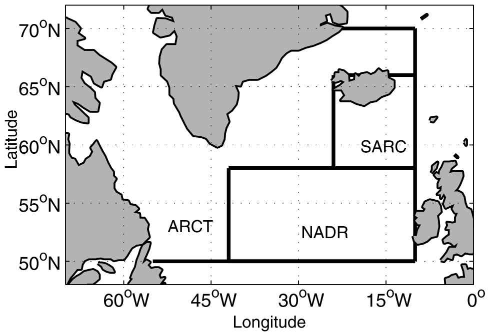

Figure 1. Map of the biogeographical provinces in the subpolar gyre.

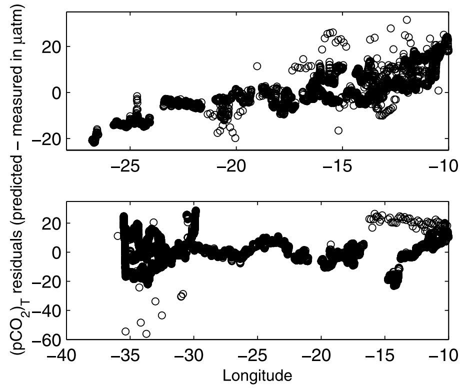

Figure 2. Difference of $(pCO_2)_T$ between the algorithm and the data for the months of February (top panel) and October (bottom panel) in the North Atlantic Drift Region.

pCO_2, $(pCO_2)_T$, and longitude, latitude, sea surface temperature (SST) and year:

$$(pCO_2)_T = A + B.Long + C.Lat + D.SST + E.Year \quad (1)$$

[6] The coefficients A, B, C, D, E and the coefficient of determination, r^2, are given in Table 1. Studying the evolution of pCO_2 with time requires data collected over several years. The coefficient of the year is better constrained when many years of data are available. However, for some months, the year could not be included in the algorithm due to the paucity of data. Sometimes, several years of data were available but on a very short time range so the year coefficient of the algorithm could not be satisfactorily constrained. No algorithm was determined in these cases. Thus the year was excluded from the NADR region, which has the best data coverage, for January, March and April. For SARC the year could be included in the regression only during May–June and for ARCT only during September. Most of the data were collected from the 1990's with a data record of 75,781 in 1997. Our empirical relationships explain between 67% and 98% of the variance in the data (the average r^2 is 0.88, Table 1, example of fits are given in Figure 2 for the months of February and October in NADR).

3. Results and Discussion

[7] Using these monthly algorithms with the monthly SST from the NCEP/NCAR reanalysis project (http://www.cdc.noaa.gov/cdc/reanalysis), seawater pCO_2 was reconstructed from 1982 to 1998 on a 1° latitude by 1° longitude grid for each month. In the NADR region we computed an annual mean pCO_2 for each year from 1982 to 1998 at each grid point after interpolating for the three missing months (January, March and April). At 50°N, 20°W, the annual mean pCO_2 increases with year with no significant yearly trend in sea surface temperature or wind speed (Figure 3). A similar pattern is observed at most grid points. Although the rate of increase of pCO_2 depends slightly on location, it depends much more on season (Figure 4). The rate of increase of seawater pCO_2 is larger in spring than in autumn.

[8] From June to September in the NADR region the mixed layer depth shallows, ranging from 20 m to 50 m [*Boyer and Levitus*, 1994], thus the surface ocean becomes isolated from the deeper layers, and CO_2 is fixed by net biological production. From April to July, the mean year-to-year seawater pCO_2 increase ranges from 2.3 to 3.5 μatm/yr from 1982 to 1998, whereas the mean atmospheric increase is around 1.5 μatm/yr. The fact that the increase is strongest during spring and summer, suggests a possible decrease of biological carbon fixation as the main cause. This decrease would be associated with a decrease in chlorophyll biomass. A quantitative comparison of ocean chlorophyll between the Coastal Zone Color Scanner (CZCS) images (1979–1986) and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) images (1997–2000) showed a decrease of chlorophyll concentrations especially in high latitude regions, believed

Table 1. Coefficients A, B, C, D and E of the Regression of $(pCO_2)_T$ as a Function of Longitude, Latitude, SST and Year With Their Standard Error, and Coefficient of Determination (r^2) of the Regression, For Each Month and Region

Region, Month	Intercept, A	Longitude, B	Latitude, C	SST, D	Year, E	r^2
NADR, Feb	−2488 ± 62	−0.42 ± 0.03	4.98 ± 0.14	−12.23 ± 0.34	1.38 ± 0.03	0.90
NADR, May	−7642 ± 163	−0.90 ± 0.02	−1.74 ± 0.05	−20.77 ± 0.11	4.14 ± 0.08	0.90
NADR, Jun	−4873 ± 114	−0.85 ± 0.04	1.30 ± 0.08	−15.64 ± 0.15	2.66 ± 0.06	0.82
NADR, Jul	−7013 ± 202	−0.025 ± 0.03	3.66 ± 0.12	−7.07 ± 0.24	3.64 ± 0.1	0.89
NADR, Aug	−3160 ± 135	−0.69 ± 0.01	0.84 ± 0.09	−11.31 ± 0.13	1.80 ± 0.07	0.95
NADR, Sep	−1297 ± 55	0.43 ± 0.013	−4.19 ± 0.03	−17.06 ± 0.07	1.05 ± 0.03	0.85
NADR, Oct	83 ± 255	−0.81 ± 0.02	4.81 ± 0.1	−10.92 ± 0.13	0.076 ± 0.1	0.96
NADR, Nov	747 ± 63	0.20 ± 0.01	−0.73 ± 0.03	−17.30 ± 0.05	−0.062 ± 0.03	0.98
NADR, Dec	−4306 ± 264	0.38 ± 0.03	−0.22 ± 0.24	−17.13 ± 0.17	2.45 ± 0.13	0.90
SARC, May	−2304 ± 105	−1.99 ± 0.2	−7.11 ± 0.55	−27.26 ± 0.42	1.64 ± 0.06	0.88
SARC, Jun	−6628 ± 1565	−8.05 ± 0.66	−14.99 ± 1.16	−22.78 ± 1.54	3.95 ± 0.8	0.67
ARCT, Sep	1505 ± 338	0.54 ± 0.06	−2.61 ± 0.12	−14.31 ± 0.16	−0.44 ± 0.17	0.84

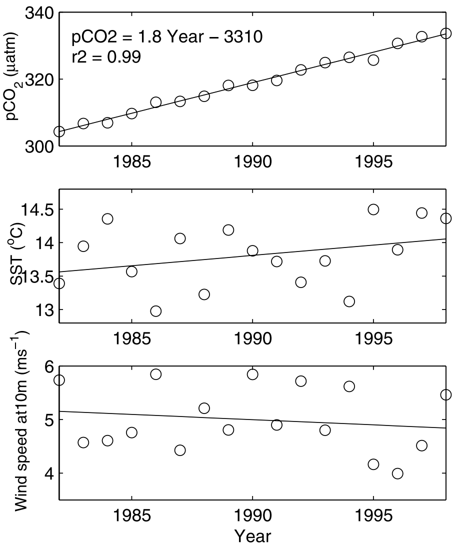

Figure 3. Mean annual pCO_2 from 1982 to 1998 in the NADR at 50°N, 20°W (top panel), corresponding sea surface temperature (middle panel) and wind speed at 10 m obtained from the NCEP/NCAR reanalysis project (bottom panel). The changes in SST and wind speed at 10 m are not statistically significant.

to be due to natural variability [*Gregg and Conkright*, 2002]. More recently *Gregg et al.* [2003] calculated primary production for the global ocean and suggested that the reduced primary production observed in the North Atlantic might represent a reduced sink of carbon via the photosynthetic pathway since the early 1980's. In addition, our analysis suggests that there has been a small increase of SST of 0.05 ± 0.03°C/yr, which would contribute to the pCO_2 increase by about 0.7 µatm/yr.

[9] From January to March there is a strong vertical mixing, particularly pronounced south of Iceland [*Pickart et al.*, 2003], with mixed layer depths reaching 600 m [*Levitus and Boyer*, 1994], which exposes older waters at the surface. Thus, the surface CO_2 concentration should reflect mainly the concentration of deeper layers isolated from the atmosphere and hence, poorer in anthropogenic CO_2. We might then expect that during this season seawater pCO_2 would remain constant or increase only slightly over time, at a rate less than the atmospheric CO_2. We are missing adequate data during January and March, but the February data indicate this is not the case, with a rate of increase significantly greater than zero. One possible explanation for the opposite pattern observed here would be a decrease in the depth of the mixing. However, no significant trend in the NCEP wind speed (http://www.cdc.noaa.gov/cdc/reanalysis) can be detected: there is a decrease of wind speed in January of −0.16 ± 0.14 m/s and an increase in February and March with a large uncertainty (0.11 ± 0.12 and 0.02 ± 0.15 respectively) from 1982 to 1998.

[10] Year-to-year pCO_2 increase is lowest during the months of October–November, whereas the trend of SST shows the largest rate of increase during this time. Summertime stratification breaks down during this season, leading to a deeper and colder mixed layer, and this is associated with an increase in surface pCO_2. We interpret the year-to-year trends in temperature and pCO_2 as indicating that this breakdown has been occurring later in the season in recent years, leading to a lower pCO_2 and higher temperatures in these months.

[11] The rate of pCO_2 increase calculated in May–June for SARC and in September for ARCT are broadly consistent with the ones obtained for the NADR region during these months. The annual increase calculated in the NADR region may therefore be representative of the annual pCO_2 increase in the subpolar gyre. The mean increase for the NADR region is slightly higher than the atmospheric CO_2 increase with an average of 1.8 µatm/yr. A seawater pCO_2 increase close to the atmospheric rate was also observed in the Barents Sea [*Omar et al.*, 2003] between 1967 and 2000.

[12] On annual average there is a slight decrease of the wind speed at 10 m of −0.043 ± 0.039 m/s and an increase of sea surface temperature of 0.048 ± 0.024°C/yr which contribute to the seawater pCO_2 increase observed during that time. The CO_2 flux is calculated as a product of the difference of pCO_2 between the ocean and the atmosphere and a gas exchange coefficient, which is mainly dependent on the wind speed. Using the monthly rates of increase of seawater and atmospheric pCO_2, the NCEP SST and wind speeds, the relationship of *Wanninkhof* [1992], we calculated that the annual carbon uptake in the NADR in 1998 was 11.2 10^{12} gC lower than in 1982, and with a decreasing trend between these two years of 8 10^{11} gC yr^{-1}(r^2 = 0.9). According to *Olsen et al.* [2003] the monthly winter uptake in the North Atlantic north of 45°N is about 10 to 15 10^{12} gC so the reduced uptake in the NADR in 1998 compared to 1982 corresponds to about one month of carbon uptake north of 45°N.

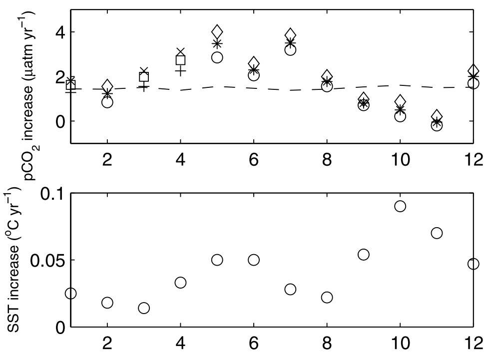

Figure 4. Top panel: Seasonal cycle of the rate of increase of seawater pCO_2 (stars) in the NADR region with minimum (open circles) and maximum values (diamonds). Squares correspond to interpolated values (January, March and April). The dashed horizontal line represents the annual mean of atmospheric pCO_2. Atmospheric xCO_2 were downloaded from the World Data Centre for Greenhouse Gases (http://gaw.kishou.go.jp/wdcgg) and are measurements from T. J. Conway and P. P. Tans (Climate Monitoring and Diagnostics Laboratory, National Oceanic and Atmospheric Administration, http://www.cmdl.noaa.gov/ccgg/index.html) at Station M (66°N, 2°E). We calculated atmospheric pCO_2 using NCEP SST and NCEP sea level pressure. Bottom panel: Seasonal cycle of the rate of increase of sea surface temperature in the NADR region.

[13] This slight decrease of the CO_2 flux contradicts the output of ocean carbon cycle models that are forced with climatological data. Such models predict a substantial and increasing uptake of carbon across the air-sea interface in the North Atlantic (J. C. Orr, personal communication, XXXX). Also, widely used syntheses of surface ocean pCO_2 data [*Takahashi et al.*, 2002] incorporate an assumption that sea-surface pCO_2 is not changing with time in high latitude regions (an assumption based on data from station P in the North Pacific). The analysis above suggests that this assumption does not hold in the North Atlantic subpolar gyre, except during the autumn season.

[14] The current generation of ocean carbon models assumes that ocean biological activity has not changed since preindustrial times. As discussed above, this may not be the case for the North Atlantic in recent decades. In fact there are several additional processes that could contribute to an increase of seawater pCO_2 over time. The increase of sea surface temperature shown in Figures 3 and 4 is one of the contributors, except in July and August when no trend appears. A decrease of deep mixing could lead to an increase of seawater pCO_2 over time by exposing younger waters than previously, but the data discussed here are insufficient to assess this process. A decrease of convection activity has been observed in the Labrador Sea but it is presently unknown whether this process also occurs in some regions of the open Atlantic Ocean and there is no clear pattern observed on the wind field that would definitely confirm this assumption. Finally, changes in the buffer capacity following import of carbon from further south could lead to a decreasing air-sea CO_2 gradient [*Anderson and Olsen*, 2002; *Wallace*, 2001].

4. Conclusions

[15] The seawater pCO_2 increase observed here is unexpected and in contradiction with predictions from climatologically driven ocean carbon cycle models. There is a clear seasonal pattern in the rate of increase, which suggests that the cause may be primarily biological in origin. This is consistent with the analysis of *Gregg et al.* [2003] who suggest a decrease of primary production. As they observe an increase at low latitudes it might imply a decrease of CO_2 sources. Our analysis highlights the need for a continuing programme to monitor the CO_2 parameters in the surface ocean, and for including interannual variability into ocean carbon models if we wish to realistically predict future changes in the oceanic sink of CO_2.

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